Recent Neutrino Experiments and Their Consistency In An Extended Harvard Model

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Abstract

We demonstrate that the solar and atmospheric neutrino data as well as the recent result of the LSND experiment cannot be satisfied simultaneously with three light neutrinos if we consider the mass degeneracy for two neutrinos in the context of an extended Harvard Model based on the gauge group $SU(2)_{qL} \times SU(2)_{lL} \times U(1)_Y$ with $S_3 \times Z_4$ discrete symmetry. Assuming two different representation contents under $S_3 \times Z_4$ symmetry for pairwise neutrinos and the lone neutrino (ν_e and ν_μ transforming as a doublet and ν_τ as singlet or ν_e and ν_τ as a doublet and ν_μ as singlet) the present model admits neutrino masses of the order of 2.8 eV and can fit either solar and atmospheric neutrino data or the LSND and solar neutrino data.

Neutrino mass is one of the key issues of the present day particle physics. Although there is no principle which dictates that the neutrino mass to be zero, the Standard Model of particle physics assumes zero mass for three generations of neutrinos. Recent experiments on the solar neutrino deficit [1], atmospheric neutrino anomaly [2], the excess of $\bar{\nu_\mu} - \bar{\nu_e}$ events observed recently by the Liquid Scintillator Neutrino Detector (LSND) experiment [3] and the need for a cosmological hot dark matter component [4] suggest that the neutrinos have non-zero mass of the order of a few eV. Wolfenstein [5] has pointed out that the LSND result combined with the Zee model [6] leads to the interesting predictions that there are two neutrinos almost degenerate with masses of interest for cosmology and a large neutrino oscillation signal should be seen on either the atmospheric neutrinos or the solar neutrinos. In other words, the atmospheric neutrino anomaly and solar neutrino deficit can be explained due to $\nu_\mu \to \nu_\tau$ and $\nu_e \to \nu_\tau$ oscillations respectively. Ma and Roy have proposed a model [7] of four light neutrinos ν_e, ν_μ, ν_τ and a singlet ν_s in the framework of $SU(2)_L \times U(1)_Y \times Z_5$ model to explain the recent data of the above mentioned experiments. They conclude that neutrino oscillation can explain the solar neutrino deficit ($\nu_e \to \nu_s$), the atmospheric neutrino anomaly ($\nu_\mu \to \nu_\tau$) and the LSND observed experiment ($\bar{\nu_\mu} - \bar{\nu_e}$). In this paper we examine the consistency of the results of the above mentioned neutrino experiments in the context of an extended Harvard model based on the gauge group $SU(2)_{qL} \times SU(2)_{lL} \times U(1)_Y$ [8] with appropriate Higgs fields and discrete symmetry, which has been recently studied to achieve spontaneous CP violation [9] and obtain neutrino mass and magnetic moment [10].

The model is based on the gauge group $SU(2)_{qL} \times SU(2)_{lL} \times U(1)_Y$ with $S_3 \times Z_4$ discrete symmetry. We concentrate on the lepton and Higgs fields of the model. The ordinary leptonic fields (l_{il}, ν_{iR}, e_{iR}, i=1,2,3), spectator fields (E_{iL}, E_{iR}, i=1,2,3) and the Higgs fields $\phi_\alpha(\alpha = 1, ..3)$, η , Σ have the following representation contents :

$$l_{iL}(1, 2, -1, 1), e_{iR}(1, 1, -2, 1), \nu_{iR}(1, 1, 0, 1), E_{iL}(1, 2, -1, 1), E_{iR}(2, 1, -1, 1),$$

$$\phi_\alpha(1, 2, 1, 0), \eta(1, 1, 0, -2), \Sigma(2, 2, 0, 0) \tag{1}$$

where the digits in the parenthesis represent $SU(2)_{qL}$, $SU(2)_{lL}, U(1)_Y$ and Lepton number L($=L_e + L_\mu + L_\tau$) respectively.

The Higgs content of the model gives rise to two step breaking of the ununified gauge group down to $U(1)_{em}$. The bi-doublet Higgs field Σ breaks the ununified gauge group down to the Standard Model and has no direct contribution to the neutrino mass matrix. The mass matrix is generated in the model through the see-saw mechanism [11] and in the (ν_L, ν_R^c) basis is given by

$$M_\nu = \begin{pmatrix} 0 & m_D \\ m_D^T & m_R \end{pmatrix} \tag{2}$$

The ϕ_α fields break the Standard model gauge group to the $U(1)_{em}$ and contribute to the 3×3 Dirac mass matrix m_D. The singlet Higgs field η leads to spontaneous lepton number violation (SLV) due to its non-zero VEV and contributes to the right-handed 3×3 Majorana mass matrix m_R. This is in contrary to the Zee model [6] in which explicit violation of lepton number occurs. However, all the SLV processes (such as $\mu \to e\gamma, K_L \to \mu e$ etc.) are

highly suppressed due to the small mass squared differences $\Delta_{ij} = m^2_{\nu_i} - m^2_{\nu_j}$ of neutrinos. Apart from the electroweak symmetry breaking scale, the present model contains two other intermediate mass scales, the ununification symmetry breaking scale and the lepton number symmetry breaking scale. It is to be noted that, the spectator fermions are necessary for anomaly cancellation [8].

We consider two different types (Type A and Type B) of transformations of the ordinary leptons under $S_3 \times Z_4$ discrete symmetry. The ordinary leptons, spectator fermions and the Higgs fields transform under $S_3 \times Z_4$ discrete symmetry as follows:

<u>Type A</u>

i) S_3 symmetry :

$$(l_{1L}, l_{3L}) \to 2, l_{2L} \to 1, (E_{1L}, E_{2L}) \to 2, (E_{1R}, E_{2R}) \to 2$$
$$(\nu_{\tau R}, \nu_{eR}) \to 2, \nu_{\mu R} \to 1, E_{3L} \to 1, E_{3R} \to 1, (\mu_R, e_R) \to 2, \tau_R \to 1,$$
$$\phi_1 \to 1, (\phi_2, \phi_3) \to 2, \eta \to 1, \Sigma \to 1 \tag{3a}$$

ii) Z_4 symmetry:

$$(\mu_R, e_R) \to -i(\mu_R, e_R), \tau_R \to -i\tau_R, (\phi_2, \phi_3) \to i(\phi_2, \phi_3) \tag{3b}$$

all other fields are invariant under Z_4 symmetry transformation.

<u>Type B</u>

i) S_3 symmetry :

$$(l_{1L}, l_{2L}) \to 2, l_{3L} \to 1, (\nu_{\mu R}, \nu_{eR}) \to 2, \nu_{\tau R} \to 1. \tag{4}$$

The rest of the fields transform as in Type A.

ii) Z_4 symmetry:

Under Z_4 symmetry all the fields transform similar to Type A.

The purpose of incorporation of S_3 permutation symmetry is to generate the equality between the Yukawa couplings and VEV's of the neutrinos. The ϕ_2 and ϕ_3 Higgs fields are necessary to achieve non-degenerate charged lepton mass matrix. The discrete S_3 symmetry also protects the diagonal form of m_R as well as gives rise to some vanishing terms in m_D, which simplifies the diagonalization of the entire mass matrix and also leads to the almost degenerate neutrino mass. The discrete Z_4 symmetry prohibits ϕ_2 and ϕ_3 Higgs fields to couple with the neutrinos and ϕ_1 Higgs field to the charged leptons. Thus, the charged lepton mass matrix becomes completely different from the neutrino mass matrix. We now concentrate on the neutrino sector. The choice of the VEV's of the neutral component of the Higgs fields are as follows:

$$< \Sigma >= \begin{pmatrix} \Sigma_1^0 & \Sigma_1^+ \\ \Sigma_2^- & \Sigma_2^0 \end{pmatrix} = \begin{pmatrix} u & 0 \\ 0 & u \end{pmatrix}, < \phi_\alpha^0 >= \begin{pmatrix} 0 \\ v_\alpha \end{pmatrix}, < \eta^0 >= x. \tag{5}$$

The VEV's of the bi-doublet and doublet Higgs fields have been fixed [9, 12] to yield the same strength of the leptonic and semi-leptonic intractions with $u = 3.5$ TeV and $\sqrt{\sum_\alpha v_\alpha^2} = 125\sqrt{2}$ GeV. The Higgs potential of the model is discussed in Ref.10 and on minimization of the potential, the relationship between x and u turns out to be

$$u = \gamma x \tag{6}$$

where γ is some combination of the coefficient of the Higgs potential. For $\gamma << 1$, we obtain the hierarchy of the VEV's of the Higgs fields as

$$x >> u >> v_\alpha. \tag{7}$$

In a previous paper [10], we have discussed the consequences of Type B transformation under $S_3 \times Z_4$ discrete symmetry on the neutrino mass. With $\gamma \sim 10^{-3}$, the Yukawa couplings g_1'(in the mass terms $(\nu_{eR}\nu_{eR} + \nu_{\mu R}\nu_{\mu R})\eta)\sim$ 1 and f_1' (in the mass terms of $(\bar{l_{1L}}\nu_{\mu R} + \bar{l_{2L}}\nu_{eR})\tilde{\phi}_1) \sim 10^{-3}$, we obtain $m_{\nu_e} = m_{\nu_\mu} = m_0' = 2.8$ eV implying $\Delta_{21} = 0$ and $\Delta_{32} = [(\frac{\xi_0^2}{\xi_0'})^2 - 1]{m_0'}^2 = 4 \times 10^{-3} eV^2$ (to explain the atmospheric neutrino anomaly) where $\xi_0 = \frac{g_2'}{g_1'}$, $\xi_0' = \frac{f_2'}{f_1'}$. f_2' and g_2' are the coefficients of the mass terms in $(\bar{l_{3L}}\nu_{\tau R}\tilde{\phi}_2)$ and $(\nu_{\tau R}\nu_{\tau R}\eta)$ respectively. Interestingly, the ratio $(\frac{\xi_0^2}{\xi_0'})$ determines the departure of the mass of ν_τ from m_0'. Thus the LSND data $(\Delta_{21} \sim (0.5 - 10)eV^2)$ cannot be explained in the model with Type B discrete symmetry. However, Type A discrete symmetry can accommodate the LSND data and we discuss its consequences now.

For Type A discrete symmetry the matrices m_D and m_R are of the form

$$m_D = \begin{pmatrix} 0 & 0 & f_1 v_1 \\ 0 & f_2 v_1 & 0 \\ f_1 v_1 & 0 & 0 \end{pmatrix} = \begin{pmatrix} 0 & 0 & a \\ 0 & \xi a & 0 \\ a & 0 & 0 \end{pmatrix} \qquad (8a).$$

where $a = f_1 v_1$ and $\xi = \frac{f_2}{f_1}$.

$$m_R = \begin{pmatrix} g_1 x & 0 & 0 \\ 0 & g_2 x & 0 \\ 0 & 0 & g_1 x \end{pmatrix} = \begin{pmatrix} b & 0 & 0 \\ 0 & \xi' b & 0 \\ 0 & 0 & b \end{pmatrix} \qquad (8b)$$

where $g_1 x = b$ and $\xi' = \frac{g_2}{g_1}$.

All the right-handed Majorana neutrinos get masses above the ununification symmetry breaking scale due to the choice of VEV's given in Eqn.(6). It may be noted that the mass matrix m_R is flavour diagonal and, hence, no transition magnetic moment can arise at the one loop level due to ordinary leptons. However, the spectator fermions can contribute to such magnetic moment of the Majorana neutrinos [10]. Furthermore, the spectator fermions allow non-zero $\nu_e - \nu_\mu$, $\nu_\mu - \nu_\tau$ mixing angles although these are zero at the tree level.

Diagonalization of the mass matrix M_ν given in Eqn.(2) leads to the following eigenvalues

$$m_{\nu i} = -\frac{{m_i}^2}{M_i} \tag{9}$$

where m_i's (i=1,2,3) are the eigenvalues of $m_D {m_D}^T$ and M_i's are the eigenvalues of m_R. Thus, we obtain the neutrino mass terms which are given by

$$m_{\nu_1} = m_{\nu_3} = -\frac{a^2}{b} = m_0 \tag{10a}$$

$$m_{\nu_2} = (\frac{\xi^2}{\xi'})m_0 \tag{10b}$$

where $m_0 = -\frac{a^2}{b}$.

With the previous choice of model parameters v_1=100 GeV, $u \sim$ 3.5TeV, $\gamma \sim 10^{-3}$, $g_1 \sim 1$, $f_1 \sim 10^{-3}$, m_0 comes out to be 2.8 eV as before. However, the model contains a tiny parameter space and there is not much freedom in the variation of the model parameters. In particular, v_1 is restricted in the

range $(100-125\sqrt{2})$GeV and $u > 3.5$ TeV in order to be consistent with the low energy charged current data.

The $(\frac{\xi^2}{\xi'})$ term lifts the neutrino mass degeneracy that can be determined from the recent LSND experiment. Thus, we obtain $(\frac{\xi^2}{\xi'})$ in the range $(0.7 - 3.16)$ and m_{ν_2} in the range (0.7- 3.16)m_0 eV. However, the atmospheric neutrino anomaly $(\Delta_{23} \sim 10^{-2})$ can not be explained in the model with Type A discrete symmetry as by fitting the LSND result we require $\Delta_{23} = \Delta_{21} \sim (0.5 - 10) eV^2$.

In summary, we conclude that an extended Harvard Model including $S_3 \times Z_4$ discrete symmetry with three light neutrinos having mass degeneracy of the order of 2.8 eV between two cannot accommodate at the same time the solar neutrino, atmospheric neutrino and the LSND data.

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References

1. K. Lande et. al. Proc. XXVth Int. Conf. on High Energy Physics, Singapore, ed. K. K. Phua and Y. Yamaguchi, World scientific (Singapore, 1991); K.S. Hirata et.al. Phys.Rev. Lett. 66, (1991) 9; P. Anselmann et. al. Phys. Lett. B285, (1992) 376; A.I. Abazov et.al. Phys. Rev. Lett. 67, (1991) 3332; V.Garvin , talk at Int. Conf. on HEP , Dallas 1992.

2. E. M. Beier et.al. Phys. Lett. B280, (1992) 149; D. Casper et.al. Phys. Rev. Lett. 66, (1991) 2561.

3. C. Athanassopoulos, et. al. Los Alamos National Laboratory, Report No. LA- UR- 95- 1238, (April 1995).

4. A. N. Taylor and M. Rowan Robinson, Nature 359, (1992) 396; M. Davis , F. J. Summers and D. Schlegel, Nature 359, (1992) 393.

5. L. Wolfenstein, CMU-HEP 95-05, DOE-ER/ 40682, May 1995.

6. A. Zee , Phys.Lett. B93 , (1980) 389.

7. E. Ma and P. Roy, UCRHEP- T145, TIFR/TH/95-17, April, 1995.

8. H. Georgi, E. E. Jenkins and E. H. Simmons, Phys. Rev. Lett. 62, (1989) 2789, 63 , (1989) 1504 (E), Nucl. Phys. B331, (1990) 541.

9. A. Ghosal, A. K. Ray and K. Bandyopadhyay Phys. Rev. D51, (1995) 1314.

10. A.Ghosal and A.K. Ray (Submitted to Phys. Rev. D).

11. M. Gell Mann, P. Ramond and R. Slansky in "Supergravity", ed. by D. Z. Freedman, (North Holland, 1979), T. Yanagida, in Proceedings of "Workshop on Unified theory and Baryon Number in the Universe" ed. by O. Sawada and A. Sugamoto, (KEK, 1979), R.N. Mohapatra and G. Senjanovic, Phys. Rev. Lett. 44, (1980) 912; Phys. Rev. D23, (1981) 165.

12. E. Ma and S. Rajpoot, Mod. Phys. Lett. A5, 979, (1990) 1529.